Patent Application
Docket No. TI -30586

ADJUSTMENT OF SLAVE FREQUENCY HOPPING PATTERN TO IMPROVE CHANNEL MEASUREMENT OPPORTUNITIES IN WIRELESS COMMUNICATIONS

This application claims the priority under 35 U.S.C. 119(e)(1) of copending U.S. provisional application number 60/181,391, filed on February 9, 2000.

FIELD OF THE INVENTION

The invention relates generally to wireless communications and, more particularly, to wireless communications that utilize frequency hopping and make frequency channel measurements.

BACKGROUND OF THE INVENTION

Present telecommunication system technology includes a wide variety of wireless networking systems associated with both voice and data communications. An overview of several of these wireless networking systems is presented by Amitava Dutta-Roy, *Communications Networks for Homes*, IEEE Spectrum, pg. 26, Dec. 1999. Therein, Dutta-Roy discusses several communication protocols in the 2.4 GHz band, including IEEE 802.11 direct-sequence spread spectrum (DSSS) and frequency-hopping (FHSS) protocols. A disadvantage of these protocols is the high overhead associated with their implementation. A less complex wireless protocol known as Shared Wireless Access Protocol (SWAP) also operates in the 2.4 GHz band. This protocol has been developed by the HomeRF Working Group and is supported by North American communications companies. The SWAP protocol uses frequency-hopping spread spectrum technology to produce a data rate of 1 Mb/sec. Another less complex protocol is named Bluetooth after a 10th century Scandinavian king who united several Danish kingdoms. This protocol also operates in the 2.4 GHz band and advantageously offers short-range wireless communication between Bluetooth devices without the need for a central network.

The Bluetooth protocol provides a 1 Mb/sec data rate with low energy consumption for battery powered devices operating in the 2.4 GHz ISM (industrial, scientific, medical)

band. The current Bluetooth protocol provides a 10-meter range and an asymmetric data transfer rate of 721 kb/sec. The protocol supports a maximum of three voice channels for synchronous, CVSD-encoded transmission at 64 kb/sec. The Bluetooth protocol treats all radios as peer units except for a unique 48-bit address. At the start of any connection, the initiating unit is a temporary master. This temporary assignment, however, may change after initial communications are established. Each master may have active connections of up to seven slaves. Such a connection between a master and one or more slaves forms a "piconet." Link management allows communication between piconets, thereby forming "scatternets." Typical Bluetooth master devices include cordless phone base stations, local area network (LAN) access points, laptop computers, or bridges to other networks. Bluetooth slave devices may include cordless handsets, cell phones, headsets, personal digital assistants, digital cameras, or computer peripherals such as printers, scanners, fax machines and other devices.

The Bluetooth protocol uses time-division duplex (TDD) to support bi-directional communication. Spread-spectrum technology or frequency diversity with frequency hopping permits operation in noisy environments and permits multiple piconets to exist in close proximity. The frequency hopping scheme permits up to 1600 hops per second over 79 1-MHZ channels or the entire ISM spectrum. Various error correcting schemes permit data

packet protection by 1/3 and 2/3 rate forward error correction. Further, Bluetooth uses retransmission of packets for guaranteed reliability. These schemes help correct data errors, but at the expense of throughput.

The Bluetooth protocol is specified in detail in Specification of the Bluetooth System, Version 1.0A, July 26, 1999, which is incorporated herein by reference.

Copending U.S. Serial No. 09/489,668 (Docket TI-30020) filed on January 24, 2000 (incorporated herein by reference) presents a Bluetooth system including a multi-antenna master which is operable to calculate weighting coefficients for its respective antennas based on channel measurements made on transmissions received by the respective antennas. These weighting coefficients are used by the master when transmitting via its plural antennas. In order to enhance the effectiveness of the calculated weighting coefficients, the master deviates from its normal frequency hopping pattern such that the transmit frequency from the master to a given slave is always the same as the transmit frequency that the slave last used to transmit to the master, which latter frequency is specified by the slave's normal frequency hopping pattern. In this manner, the master has an opportunity to measure the channel between the master and the slave at the same frequency that the master will soon use for its next transmission to that slave. This channel measurement opportunity soon before the next master transmission to the slave, and on the same frequency that the master will use in that

transmission, increases the effectiveness of the calculated weighting coefficients that will be used in the transmission to the slave.

However, the fact that the master does deviate from its normal frequency hopping pattern in the above-described operation presents some disadvantages. For example, if the master wishes to address an ACL (Asynchronous Connection-Less) slave while using an SCO (Synchronous Connection-Oriented) link, the master would use the frequency dictated by its normal frequency hopping pattern, but the SCO slave would be listening on the frequency that it last used to transmit to the master. Accordingly, the SCO slave will not receive the expected packet, and will therefore respond with a negative acknowledgment (NAK in Bluetooth) indicating that the expected packet was not received. This negative acknowledgment will disadvantageously collide with the ACL slave's response to the master's transmission. A similar problem could arise if the master attempts to send an ACL broadcast packet on an SCO link.

It is therefore desirable to avoid the above-described collision problem while still providing the master with the aforementioned channel measurement opportunity.

The present invention avoids the above-described collision problem for SCO links by appropriately modifying the slave's frequency hopping pattern such that each slave-to-master transmission is on the same frequency that the master's normal frequency hopping

pattern specifies for the master's next transmission (or for one of the master's next several transmissions) to that slave. In this manner, the aforementioned collision problem is avoided, because the master's normal frequency hopping pattern advantageously remains unchanged. Furthermore, the aforementioned channel measurement opportunity is retained, because the master still advantageously receives the slave's transmission on a frequency that the master will soon use for transmission to the slave.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 diagrammatically illustrates one example of how a slave frequency hopping pattern can be modified according to the invention.

FIGURE 2 diagrammatically illustrates another example of how a slave frequency hopping pattern can be modified according to the invention.

FIGURE 3 diagrammatically illustrates a further example of how a slave frequency hopping pattern can be modified according to the invention.

FIGURE 4 diagrammatically illustrates pertinent portions of an exemplary embodiment of a master device according to the invention.

FIGURE 5 illustrates exemplary operations which can be performed by the master device of FIGURE 4.

FIGURE 6 diagrammatically illustrates pertinent portions of an exemplary embodiment of a slave device according to the invention.

FIGURE 7 illustrates exemplary operations which can be performed by the slave device of FIGURE 6.

FIGURE 8 illustrates further exemplary operations which can be performed by the master device of FIGURE 4.

DETAILED DESCRIPTION

FIGURE 1 diagrammatically illustrates one example of operations according to the present invention. The example of FIGURE 1 relates to transmission of Bluetooth HV1 (High-quality Voice) packets between a master device M and a single slave device S. According to the invention, the slave device S transmits to the master M on the same frequency that the master will next transmit to the slave device according to the master's normal frequency hopping pattern. Thus, the master is advantageously given the opportunity to make channel measurements on frequencies f_3, f_5 and f_7 immediately before transmitting on those respective frequencies, but without requiring the master to deviate from its own normal frequency hopping pattern. Therefore, the slave S can listen for the master's transmission on the frequency specified by the master's normal frequency hopping pattern, thus permitting the master to transmit to an ACL slave (or to transmit an ACL broadcast packet) without the above-described collision problem.

FIGURE 2 illustrates another example of operations according to the present invention. FIGURE 2 relates to transmission of Bluetooth HV3 packets between a master M and three slaves S_1, S_2 and S_3. In this example, each of the slaves transmits to the master on the same frequency that the master will use (as dictated by the master's normal frequency hopping pattern) on its next transmission to that particular slave. For example, after

receiving a transmission from the master on f_1, the slave S_1 transmits to the master on frequency f_7, which is the frequency that the master will use (as specified by the master's normal frequency hopping pattern) for its next transmission to slave S_1. Accordingly, the master is given an opportunity to make measurements on the frequency (for example f_7) that it will soon (five time slots later in this example) use for transmission to the slave.

FIGURE 3 illustrates a further example of operations according to the present invention. The example of FIGURE 3 relates to transmission of Bluetooth HV3 packets between a master and three slaves S_1, S_2 and S_3. However, unlike the example of FIGURE 2, only the frequency hopping pattern of slave S_1 is modified, the other two slave devices S_2 and S_3 retaining their normal frequency hopping patterns. Again, as shown in FIGURE 3, the transmission from S_1 on f_7 gives the master M an opportunity to measure on the frequency that it will soon (five time slots later) use for transmission to slave S_1.

In each of the examples of FIGURES 1-3, the master M does not deviate from its normal frequency hopping pattern, but is still given an opportunity to make measurements on slave-to-master frequencies that it will soon use for master-to-slave transmissions. Thus, the master can calculate weighting coefficients that will provide meaningful control of near-future transmissions, while advantageously retaining the capability of addressing an ACL slave (or slaves) while using an SCO link. In the examples of FIGURES 1-3, a given slave

transmits to the master on the frequency that the master is scheduled to use for its next transmission to that slave. However, the aforementioned meaningful measurement opportunity benefit of the invention can be realized so long as the slave transmits to the master on a frequency that is scheduled for one of the master's next several transmissions to the slave, for example one of the master's next ten transmissions to the slave.

FIGURE 4 diagrammatically illustrates pertinent portions of an exemplary embodiment of a (e.g., Bluetooth) master device according to the invention. Examples of the master device are mentioned above. The master device of FIGURE 4 includes a wireless communications interface 41 coupled to a communication signal processing portion 43 for exchanging therewith communication information. The wireless communications interface 41 can use well-known conventional techniques to interface the communication signal processing portion 43 to a wireless communications link 45 (for example a Bluetooth radio link) via a plurality of antennas 47. The link 45 is used for bidirectional communications with one or more slave devices. The wireless communications interface 41 includes a channel measuring portion 42 which can perform conventional quality measurements on communications received via the respective antennas at 47. The wireless communications interface 41 further includes a weighting coefficients calculator 44 coupled to the channel measuring portion 42, and responsive to the conventional quality measurement information

produced by the channel measuring portion 42 for calculating appropriate weighting coefficients associated with the respective antennas at 47 for use in transmissions to the slave device(s). As one example, if all but one weighting coefficient are zero, then only the antenna associated with the non-zero coefficient would be used for a transmission to the slave device.

The master device of FIGURE 4 further includes a next slave-to-master (SM) frequency information register 46 for storing therein information indicative of the frequency that will be used for the next slave-to-master transmission. This register is an indicator of the next SM transmission frequency. The output 48 of register 46 makes this information available to the wireless communications interface 41. A load input 49 of the register 46 is coupled to the wireless communications interface 41 to receive therefrom an indication that the jth frequency in the master's normal transmit frequency hopping pattern has been used by the interface 41 to transmit a communication to the slave device. This jth master-to-slave frequency is designated herein as MS_j. The data input 40 of the register 46 is coupled to the wireless communications interface 41 to receive therefrom information indicative of the frequency that the master's normal transmit frequency hopping pattern specifies for the next (the (j+1)th) master-to-slave transmission. This frequency is designated herein as MS_{j+1}. Thus, as shown in FIGURE 4, when the jth master-to-slave frequency MS_j has been used to

transmit to the slave, information indicative of the (j + 1)th master-to-slave frequency MS_{j+1} is loaded into the register 46. This information in register 46 indicates to the wireless communications interface 41 that the next slave-to-master frequency will be frequency MS_{j+1} from the master's normal transmit frequency hopping pattern. Thus, the interface 41 will receive the next slave-to-master transmission on MS_{J+1}.

Relating the example of FIGURE 4 to the example of FIGURE 1, f_1 in FIGURE 1 corresponds to j = 1 in FIGURE 4, f_3 in FIGURE 1 corresponds to j = 2 in FIGURE 4, f_5 in FIGURE 1 corresponds to j = 3 in FIGURE 4, etc. Relating the example of FIGURE 4 to slave S_1 in FIGURE 2, f_1 in FIGURE 2 corresponds to j = 1 in FIGURE 4, f_7 in FIGURE 2 corresponds to j = 2 in FIGURE 4, etc. Relating FIGURE 4 to slave S_2 in FIGURE 2, f_3 in FIGURE 2 corresponds to j = 1 in FIGURE 4, f_9 in FIGURE 2 corresponds to j = 2 in FIGURE 4, etc. Relating FIGURE 4 to slave S_3 in FIGURE 2, f_5 in FIGURE 2 corresponds to j = 1 in FIGURE 4, f_{11} in FIGURE 2 corresponds to j = 2 in FIGURE 4, etc. Relating FIGURE 4 to slave S_1 of FIGURE 3, f_1 in FIGURE 3 corresponds to j =1 in FIGURE 4, f_7 in FIGURE 3 corresponds to j = 2 in FIGURE 4, etc. Thus, for a given slave, whenever the jth frequency for transmission to that slave has been used, information indicative of the (j + 1)th frequency for transmission to that slave is loaded into register 46, thereby indicating

that this (j + 1)th frequency will be used for the next transmission from the slave to the master.

FIGURE 5 illustrates exemplary operations which can be performed by the master device of FIGURE 4. At 51, the jth master-to-slave (MS) transmission is performed on frequency MS_j (and using weighting coefficients for the respective master antennas). Thereafter at 52, frequency MS_{j+1} is designated as the next slave-to-master frequency. Thereafter at 53, the jth SM transmission is received on frequency MS_{j+1}. At 54, channel measurements are made on the jth SM transmission (e.g., RSSI (received signal strength indicator), Bluetooth sync word correlation value), and weighting coefficients for use in the (j+1)th MS transmission are calculated based on the channel measurements. Thereafter, the index j is incremented at 55, and the above-described operations at 51-54 can be repeated.

FIGURE 6 diagrammatically illustrates pertinent portions of an exemplary embodiment of a (e.g., Bluetooth) slave device according to the present invention. Examples of the slave device are mentioned above. The slave device of FIGURE 6 includes a wireless communications interface 61 coupled for exchanging communication information with a communications signal processing portion 63. The wireless communications interface 61 interfaces the communications signal processing section 63 to a wireless communications link 65 via an antenna 62 for bidirectional wireless communications with a master device

such as shown, for example, in FIGURE 4. Similarly to the operation described above with respect to FIGURE 4, when the wireless communications interface 61 indicates at 68 that the jth master-to-slave frequency MS_j has been used by interface 61 to receive a communication from the master device, information indicative of the frequency MS_{j+1} is loaded into a register 66, thereby indicating to the wireless communications interface 61 that frequency MS_{j+1} from the master's normal transmit frequency hopping pattern is to be used by interface 61 for the next slave-to-master transmission. Thus, register 66 is an indicator of the next SM transmission frequency.

FIGURE 7 illustrates exemplary operations which can be performed by the slave device of FIGURE 6. At 71, the jth master-to-slave transmission is received on frequency MS_j. At 72, frequency MS_{j+1} is designated as the next slave-to-master transmission frequency. At 73, the jth slave-to-master transmission is performed on frequency MS_{j+1}. After incrementing the index j at 74, the aforementioned operations at 71-73 can be repeated.

Referring again to FIGURE 5, the quality measurements made at 54 can be used for purposes other than calculating weighting coefficients for multiple antennas, for example, selecting transmission parameters such as the channel coding rate (e.g., use higher coding rates in better quality conditions), the packet length (e.g., use longer packets in better quality conditions), and the transmission power level (e.g., use lower power in better quality

conditions). This is shown generally at 54A in FIGURE 8. It will be recognized that this type of transmit parameter selection operation is applicable even in devices that utilize only a single antenna, and the selection can be performed, for example, by the wireless communications interface 41 of FIGURE 4.

It will be evident to workers in the art that the embodiments of FIGURES 1-8 can be implemented, for example, by suitable modifications in hardware, software, or a combination of hardware and software, in conventional frequency hopping wireless communication devices, for example Bluetooth master and slave devices.

Although exemplary embodiments of the invention are described above in detail, this does not limit the scope of the invention, which can be practiced in a variety of embodiments.